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The steady state distribution of $e^{\pm}$ pairs formed by $p-p$ collisions and high energy spectrum in galactic black hole systems

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Relativistic non-thermal protons, if produced in the inner region of the accretion disk around a black hole, will produce electrons, positrons and gamma photons through interaction with ambient matter. Electrons and positrons lose energy via Coulomb and inverse Compton (IC) processes. We relax the assumption that, in case of IC process, change in energy of particle in single collision is much less than the energy of the particle itself. The steady state distribution of electrons and positrons are computed by solving an integro-differential equation where the pair production and pair annihilation are self-consistently treated. Resultant particle and photon spectra are calculated for parameters pertaining to the soft and hard state of black hole binary systems to predict the signature of high energy protons in photon spectrum of black hole binaries. Results obtained from the model are compared with the observed data for $Cyg\ X-1$.

1. Introduction

Black hole x-ray binaries are generally found in two spectral states : hard state and soft state. In the hard state, the spectrum can be described by a hard power-law ($\Gamma \sim 1.7$) and a cut-off at 100 keV. The broadband x-ray spectrum can be modelled with Comptonization of soft photons from the accretion disk by thermal electrons with temperature $T \approx 50$ keV and optical depths of order of unity [1]. In the soft state, the source spectrum consists of a blackbody-like soft component with $kT \approx 1$ keV and a power-law component extending upto 1 MeV with no detectable cut-off [2]. Soft state spectrum is generally modelled in the frame work of "hybrid model" [3] where it is considered that the soft photons are Comptonized by the thermal and non-thermal electrons that coexist in the emission region. The blackbody-like soft component in the spectrum is produced due to the Comptonization by thermal electrons while the non-thermal electrons produce the power-law tail of the photon spectrum [4]. However the acceleration process that produces non-thermal electrons is largely unknown. If this process is independent of the mass of the particle, then protons may also be accelerated in the inner region of the accretion disk.

In this work an attempt is made to find out the signature of hadrons in the photon spectrum of black hole binaries. It is assumed that protons are accelerated to a non-thermal distribution in the inner region of the accretion disk. Relativistic protons can undergo inelastic collisions with thermal proton in the background plasma to produce charged and neutral pions which in turn decay into electrons/ positrons and γ-rays respectively. The electrons and positrons produced in this process are primarily at high energies. Electrons and positrons lose energy due to inverse Compton process in the background photon field and also due to Coulomb scattering with the background thermal plasma in the inner region of the accretion disk. The steady state spectrum of the electron and positron are obtained by solving an integro-differential equation. The resultant electrons and positrons produce high energy γ-ray photons by inverse Compton process. An important effect, considered here, is the pair production of γ-ray photons in interaction with copious photons in the inner region of accretion disk. At this point this work differs fom the previous works [5] to compute the spectra of non-thermal electron distribution due to pion decay. We limit our study for plasma which is not pair dominated. In §2 we describe the formalism of our model. Results and conclusion of the work are described in §3 and §4 respectively.

2. Formalism

We consider a uniform sphere of nonrelativistic thermal plasma with number density n_T and radius R. The photon component inside the plasma is given by $n_{\gamma,ph}(e)$ (where $e \equiv h\nu/m_e c^2$ is the normalised photon energy) and normalization is determined such that the photon energy density

$$U_{\gamma,ph} = m_e c^2 \int_0^\infty e n_{\gamma,ph}(e) de = \frac{l_{ph}(1+\tau) m_e c^2}{4\pi R \sigma_T} \quad (1)$$

where l_{ph} is the compactness of the photon component and $\tau = n_T \sigma_T R$ is the Thompson optical depth. In case of soft state, $n_{\gamma,ph}(e)$ is taken as a Wien peaked photon density at temperature kT_{ph} and, in case of hard state, it is taken as power-law with an exponential cut-off at energy E_c ($\approx$ 100 keV). As the acceleration process is largely unknown, in our model the normalization of the non-thermal proton spectrum is determined from ratio (β) of the total compactness of the electrons, positrons and gamma-rays (l_{p-p}) produced in the $p-p$ collisions to the compactness of the photons (l_{ph}) inside the plasma. The proton spectral index α is taken as greater than 2. Relativistic protons interact with the thermal background plasma and produce electrons, positrons and γ-rays. Electrons and positrons interact with the background photons with energy $\approx$ 100 keV in the hard state and $\approx$ 3 keV in the soft state. The interactions predominantly takes place in the Klein-Nishima regime.

The steady state positron particle density $N_+(\gamma)$ is determined by solving the integro-differential equation

$$\frac{\partial}{\partial\gamma}(\dot{\gamma}_C N_+(\gamma)) + N_+(\gamma)\int_1^\gamma d\gamma' P(\gamma,\gamma') - \int_\gamma^\infty d\gamma' P(\gamma',\gamma) N_+(\gamma') + \dot{N}_+(\gamma) = Q_{+,pp}(\gamma) + Q_{+,\gamma\gamma}(\gamma) \quad (2)$$

while the electron particle density $N_-(\gamma)$ is obtained from

$$\frac{\partial}{\partial\gamma}(\dot{\gamma}_C N_-(\gamma)) + N_-(\gamma)\int_1^\gamma d\gamma' P(\gamma,\gamma') - \int_\gamma^\infty d\gamma' P(\gamma',\gamma) N_-(\gamma') = Q_{-,pp}(\gamma) + Q_{-,\gamma\gamma}(\gamma) \quad (3)$$

$Q_{\pm,pp}$ are the rates of production of positrons and electrons in $p-p$ collision and $Q_{\pm,\gamma\gamma}$ are the rates of production positrons and electrons in $\gamma\gamma$ interaction. $\dot{\gamma}_C$ is the Coulomb loss rate for the particles. $P(\gamma, \gamma - e)dedt$ is the probability that a positron/electron with Lorentz factor γ will suffer a collision and its Lorentz factor changes by an amount between e and $e + de$ in time dt.

The equilibrium photon density $n_\gamma(e)$ inside the sphere is a solution of

$$Q_{\gamma,IC} + Q_{\gamma,pp} + Q_{\gamma,e^+e^-} = n_\gamma(e)\Big[R_{\gamma\gamma} + \frac{c}{R[1+\tau_{KN}(e)]}\Big] \quad (4)$$

where $R_{\gamma\gamma}(e)$ is the rate of photon annihilation. $Q_{\gamma,IC}$, $Q_{\gamma,pp}$ and Q_{γ,e^+e^-} are the photon production rates due to inverse Compton, $p-p$ interaction and pair annihilation respectively. τ_{KN} is the Klein-Nishima optical depth in the escape term for photons. $Q_{+,pp}$, $Q_{-,pp}$ and $Q_{\gamma,pp}$ are evaluated using the energy dependent cross-sections given by Eliek and Kafatos (1983). Equation (2), (3) and (4) are solved self-consistently to obtain electron and positron distributions as well as the radiative flux as a function of four parameters : Thomson optical depth τ, photon compactness l_{ph}, β, and non-thermal proton index α. The results are insensitive to the size of the source region R.

3. Results

The computed spectra for different values of β are shown in Figures 1 and 2 for the soft and hard states respectively. The other parameters are taken similar to what is generally found in the soft and hard states of a

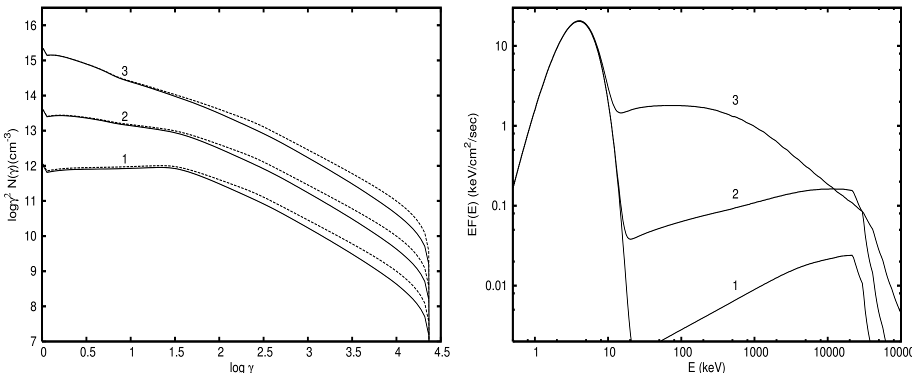

Figure 1. Computed particle (*left panel*, bold : electron; dashed : positron) and photon spectra (*right panel*) for soft for $\beta = 0.001$, 0.01 and 0.1, labeled as 1, 2 and 3 respectively. The other parameters are $l_s = 250$, $kT_{ph} = 1$ keV, $\tau = 2.5$ and $\alpha = 2.5$.

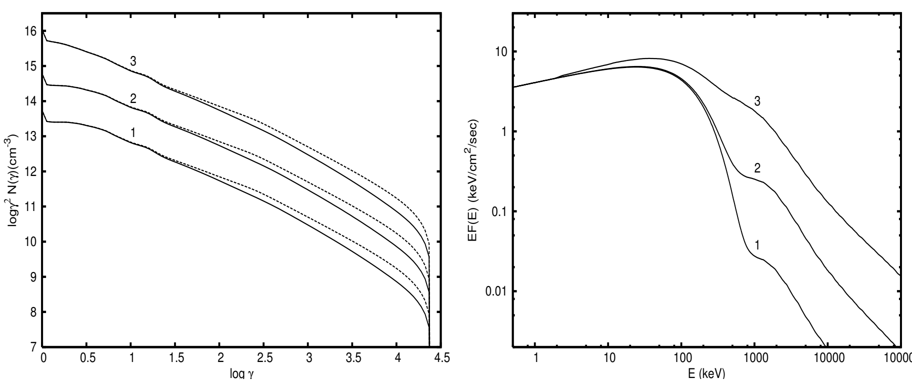

Figure 2. Computed particle (*left panel*, bold : electron; dashed : positron) and photon spectra (*right panel*) for hard state for $\beta = 0.001$, 0.01 and 0.1, labeled as 1, 2 and 3 respectively. The other parameters are $l_s = 250$, $E_c = 100$ keV, $\tau = 1.0$ and $\alpha = 2.5$.

typical galactic black hole system. In the soft state, high energy photons produced by the the inverse Compton process interact with the soft photons of energy ~ 3 keV to generate $e^{\pm}$ pairs. This gives a cut off in the non-thermal photon spectrum at ~ 80 MeV. As the photon energy in the plasma in the hard state is much higher (typically, 100 keV), so the cut-off in the photon spectrum appears nearly at 3 MeV. As we increase β for a given l_{ph} (which essentially implies acceleration of more number of protons into relativistic energies) the number density of γ-ray photon increases, and pairs are also produced by the self interaction. This causes spectral breaks in the spectrum at different energies which is evident from the spectrum. In Figures (1) and (2), l_{p-p} takes values 0.3, 3, and 30. Thus, in the soft state, the spectrum has a broad feature around $1-10$ MeV region. In the hard state, the spectral component has a different slope compared to intrinsic photon spectrum inside the plasma, but it falls off rapidly due to $\gamma - \gamma$ pair production. The broad feature of the spectrum around $1-10$ MeV in the soft state may be detected by the future observations by $GLAST$. Presently we use $OSSE$ and $COMPTEL$ data for $Cyg\ X-1$ to constrain the power in injected proton in the source. We have considered soft as well as hard state data for $Cyg\ X-1$. McConnel et al (2002) fitted the soft and hard state

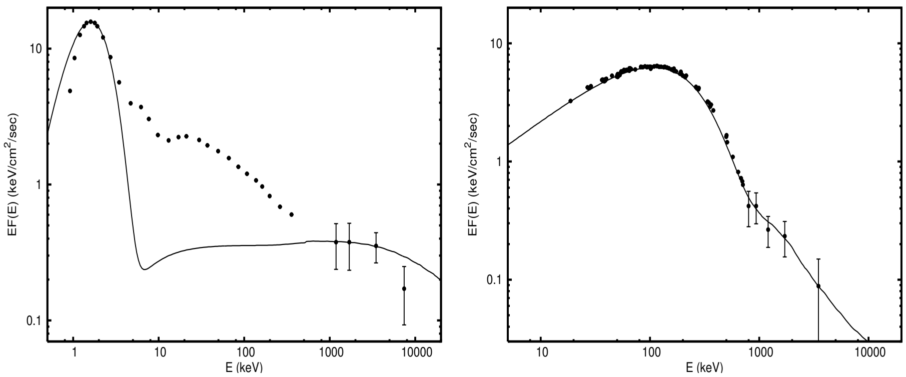

Figure 3. Soft state (*left panel*) and hard state (*right panel*) data of $Cyg\ X-1$ during 1996. The MeV data of the spectrum is fitted with present model.

data with EQPAIR model. This does not give a good fit of the power-law component in MeV region. Using the present model we fit the existing data in MeV region in the soft and hard state and predict its behaviour in the $1-10$ MeV range. Fitting of the data shown in Figure 3. The power required for proton to fit the spectra soft state is $\approx 10^{37}$ ergs s^{-1} whereas the luminosity of electrons as determined by McConnell et al (2002) using EQPAIR model is 6.7×10^{36} ergs s^{-1}. In the hard state, proton luminosity comes as $\sim 1.35 \times 10^{36}$ ergs s^{-1} and non-thermal electron luminosity as obtained from EQPAIR model is $\sim 2.4 \times 10^{37}$ ergs s^{-1}. This clearly indicates that protons might be accelerated in the inner region of the accretions disk and contribute to the spectrum in the MeV region while non-thermal relativistic electrons contribute to the spectrum in the soft-to-hard x-ray region of the spectrum.

4. Conclusion

It is shown that the non-thermal protons, if present in the inner region of the accretion disk of a black hole binary, will contribute a detectable amount of flux in the high energy γ-ray range of the photon spectrum. In the soft state, photon spectrum from the source is predicted to have a broad feature in the $1-10$ MeV energy range which can be verified with the observations from $GLAST$. Detection of such a feature will help to constrain the acceleration mechanism in the inner region of the accretion disk. The Present model has been used to fit the observed MeV spectrum from $Cyg\ X-1$ and it is shown that the required proton luminosity is of the same order of the electron luminosity obtained from the EQPAIR model. This indicates the possibility that the protons are also accelerated in the accretion disk environment.

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